§9. Study of the Burn Control of the High Density Plasma in the FFHR Helical Reactor

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Recently a high-density plasma regime has been observed in Large Helical Device (LHD) experiments [1]. From these experimental results, the high-density and low-temperature operation may be a promising scenario to realize a helical reactor. However, in such a situation the ignited operation usually faces thermal instability, where the operating point moves to the higher-temperature and lower-density regime. Many stabilizing methods of the thermally unstable ignition point have been proposed, where zero-dimensional equations of the particle and power balance equations have been linearized around the unstable operating point, and then stabilizing techniques are used. but access to the unstable operating point from the zero temperature and density has not been demonstrated.. Therefore, it may be difficult to apply it to the actual situation.

To overcome above difficulties, in this study we proposed a new control method to stabilize the thermally unstable operating point without any linearization and with the proportional-integration-derivative (PID) control of the fueling based on the total fusion power, capable of access to the operating point from the zero temperature and density.

In the D-T particle balance equation, the proportional-integration-derivative (PID) control of D-T fueling is used for feedback control of the fusion power as

$$S_{DT}(t) = S_{DT0}\left\{e_{DT}(P_f) + \frac{1}{T_{\rm int}}\int_0^t e_{DT}(P_f)dt + T_d\frac{de_{DT}(P_f)}{dt}\right\}G_{fo}(t) \quad (1)$$

where T_{int} is the integration time, T_d is the derivative time, and the error of the fusion power is $e_{DT}(P_f) = c(1- P_f/P_{fo})$ with c=+1 for the stable boundary, c=-1 for the unstable boundary. $P_{fo}(t)$ the fusion power set value and $P_f(t)$ the calculated fusion power. $S_{DT}(t)$=0 is set in the program when $S_{DT}(t)$<0 is required in Eq.(1). The helium ash confinement time ratio of $\tau_\alpha*/\tau_E$=3 and the ISS95 confinement scaling are used, where γ_{ISS}=1.92 represent the confinement enhancement factors over the ISS95 scaling,. We have used the parameters of the FFHR (R=14m, a=1.73m, B_o=6T, P_f=1.9 GW, and the parabolic density and temperature profiles).

The operating path corresponding to Fig. 1 is plotted on POPCON in Fig. 2. It can be clearly seen that the operating point proceeds to the thermally unstable operating point from the early phase. Final operating parameters are the temperature of $T(0)$=8.5 keV (15.3 keV), the density of $n(0)$=6x10^{20} m^{-3} (2.8x10^{20} m^{-3}), the beta value of $<\beta>$= 3.5% (3.0), and the confinement time of τ_E=3.9 s (1.9s). The values in parentheses describe the ones for the stable operating point for the same fusion power. It should be noted that the confinement time is improved in the high density regime, then the plasma conduction loss is decreased , the divertor heat load is decreased. The beta bale is slightly increased, which means the larger plasma energy than the stable operating point for the same fusion power.

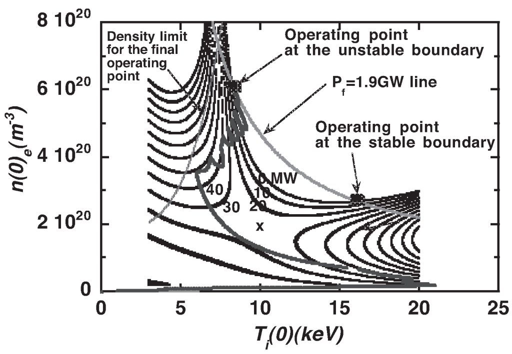

Fig. 1. Operation path (blue) to the unstable ignition point on POPCON. Transition to the unstable point is set at 30 s.

This stabilizing mechanism is understood as shown in POPCON in Fig. 2. When P_f is larger than P_{f0}, the operating point (A) moves toward the higher density and shifts to the higher temperature side due to ignition nature. When it enters in the sub-ignition regime (B), it goes to the lower temperature side due to sub-ignition nature and crosses the constant P_{fo} line (C). The fueling is now decreased, and the operating point proceeds to the lower-density and higher-temperature side, and goes into the ignition regime (D), and crosses the constant P_{fo} line.

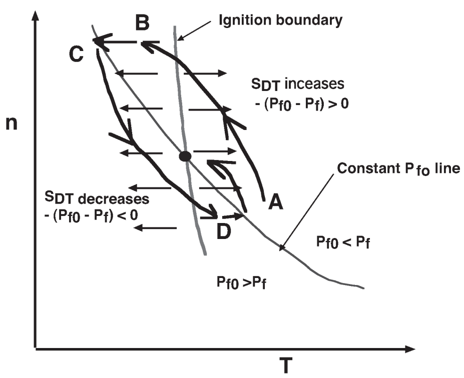

Fig. 2 Schematic movement of the operating point around the unstable ignition point on POPCON.

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